

# Leptophobic $U(1)$ 's and $R_b$ , $R_c$ at LEP

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In the context of explaining the experimental deviations in  $R_b$  and  $R_c$  from their Standard Model predictions, a new type of  $U(1)$  interaction is proposed which couples only to quarks. Special attention will be paid to the supersymmetric  $\eta$ -model coming from  $E_6$  which, due to kinetic mixing effects, may play the role of the leptophobic  $U(1)$ . This talk summarizes work done with K.S. Babu and J. March-Russell in Ref. [ 1].

## 1. Introduction

The central lesson which one begins to draw after any preliminary examination of the data coming from the four experiments at LEP is that the Standard Model (SM) is in very good shape. In particular, some of the leptonic measurements at LEP are showing agreement with the SM to nearly 1 part in 1000, a level of accuracy unusual in high energy experiments. Nonetheless there are two, by now well known, nagging discrepancies between the LEP data and the SM, both in the  $Z^0$  hadronic decay branching fractions. Defining  $R_q \equiv \Gamma(Z \rightarrow q\bar{q})/\Gamma(Z \rightarrow \text{hadrons})$ , one has [ 2]:

$$R_b = \begin{cases} 0.2215 \pm 0.0017 & (\text{LEP}) \\ 0.2152 \pm 0.0005 & (\text{SM}) \end{cases} \quad (1)$$

$$R_c = \begin{cases} 0.1596 \pm 0.0070 & (\text{LEP}) \\ 0.1714 \pm 0.0001 & (\text{SM}) \end{cases} \quad (2)$$

where the theoretical uncertainties are dominated by the uncertainty in the top quark mass,  $m_t = (176 \pm 13) \text{ GeV}$ . There is thus a  $3.7\sigma$  excess in  $R_b$  and a  $1.7\sigma$  deficit in  $R_c$ .

There are a number of plausible solutions to the current disagreement, not least of which is simple experimental error.  $R_b$  alone can be corrected (at least partially) by low-energy supersymmetry (SUSY)[ 3], but this has no bearing on  $R_c$ . Solutions have also been proposed in which new fermions mix with the SM fermion spectrum.

The most attractive of these solutions proposes that the "top" quark observed at FNAL is actually a new fourth generation  $t'$ -quark, while the real  $t$ -quark (defined to be the  $SU(2)$  partner of the  $b$ -quark) is hiding near the  $Z$ ,  $m_t \approx m_Z$  [ 4]; this solution again does not affect  $R_c$ .

I propose instead an additional  $U(1)_X$  interaction whose corresponding gauge boson,  $X$ , mixes with the usual  $Z$ , thereby changing the interactions of the  $Z$  with the SM fermions. Specifically I will build realistic models in which the  $Z$ - $X$  mixing can resolve both the  $R_b$  and  $R_c$  problems without upsetting the other LEP observables; and in particular I will show that there exists a model coming from  $E_6$  which is phenomenologically acceptable.

## 2. Constraints on $U(1)_X$

Any realistic model of new physics which attempts to resolve the  $R_b$  and  $R_c$  anomalies must confront two difficulties. The first difficulty arises if one wants to assign interactions to the  $b$  and  $c$ -quarks which are not generation-independent, *i.e.*, change the predictions for only  $R_b$  and  $R_c$ . In that case one would generically expect large flavor-changing neutral currents (FCNC's) through violation of the GIM mechanism, particularly in the  $D^0$ - $\bar{D}^0$  system. The solution may lie within the simple observations that, for  $\Delta R_q \equiv R_q^{LEP} - R_q^{SM}$ ,  $3\Delta R_b + 2\Delta R_c = -0.0047 \pm 0.0134$ , consistent with zero, and that the total hadronic width at LEP agrees well with the SM. Such a pattern of shifts is indicative of a universally-coupled, generation-independent  $X$ -boson:

$$\Gamma_{u,c} = \Gamma_{u,c}^{SM} + \Delta\Gamma_c \quad (3)$$

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$$\Gamma_{d,s,b} = \Gamma_{d,s,b}^{SM} + \Delta\Gamma_b. \quad (4)$$

By having generation-independent couplings, one does not violate the GIM mechanism and no new large FCNC's are generated. We will therefore demand this generation-independence as the first of four principles we will require of any model we build.

The second difficulty is that the leptonic data at LEP is all very precisely measured, and in strong agreement with the SM. If the leptons are charged under  $U(1)_X$  then there should appear discrepancies in their partial widths of roughly the same size as those in the quark sector, an effect that is clearly not observed. Thus we must demand that the  $U(1)_X$  charges of the leptons be zero (or very small), leading us to name such interactions *leptophobic*. This leptophobia will be our second principle for model-building.

Using a leptophobic  $U(1)$  to explain the  $R_b$  and  $R_c$  anomalies was shown to be phenomenologically viable in Ref. [5]. Though the authors did not build specific anomaly-free gauge models, there were able to show that the  $Z$ - $X$  mixing arising in such a model could in principle explain the LEP data. In contrast to [1], the authors of [5] also attempted to explain a possible anomaly in the CDF jet cross-section at high  $p_T$ . This added requirement led them to consider models which are very different than those considered here and in [1]: the “models” of [5] have heavy ( $\sim 1$  TeV)  $X$ -bosons and are strongly coupled, while the models I am considering here have light ( $\sim m_Z$ )  $X$ -bosons and are weakly coupled.

We will impose two further constraints on the models we build, though these are slightly more prejudicial. We will require that all new matter which is added to the model (*e.g.*, for anomaly cancellation) be vector-like under the SM gauge groups. This means that the new matter will all receive masses at the scale of the  $U(1)_X$  breaking, which is presumably above the weak scale. We also require that the SM gauge couplings unify near  $10^{16}$  GeV, a behavior expected in grand unified (GUT) and string theories and observed in the minimal SUSY model (MSSM). This will further restrict our new matter to come in complete multiplets of an ersatz  $SU(5)$  (it is ersatz because

the  $SU(5)$  need not commute with  $U(1)_X$ ).

Under the conditions laid out above, we built models which fall into two broad classes [1]. In the first, there are models with extra matter whose charges have been chosen specifically to cancel the  $G_{SM} \times U(1)_X$  anomalies. Such models could in principle derive from a string theory, but they do not have the attraction of coming from a simple GUT group. The second class of models are models which do come from simple GUT's. That such a model even exists seems at first improbable since GUT's tend to place quarks and leptons in common representations, giving charges to quarks and leptons alike under the GUT subgroups and ruining leptophobia. However I will explain in the remaining part of this talk just how, in one example, one can indeed get a leptophobic  $U(1)_X$  from a common GUT group, namely  $E_6$ . But to do so I must return to the basics of how two abelian gauge bosons can mix with one another.

### 3. $U(1)$ Mixing in an Extended SM

The most general Lagrangian for the gauge sector of a  $SU(2)_L \times U(1)_Y \times U(1)_X$  theory can be written:

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} \\ & + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \frac{1}{2}m_X^2 X_\mu X^\mu \\ & - \frac{1}{2}\sin\chi X_{\mu\nu}B^{\mu\nu} + \Delta m^2 Z_\mu X^\mu, \end{aligned} \quad (5)$$

where  $W_{\mu\nu}$ ,  $B_{\mu\nu}$  and  $X_{\mu\nu}$  are the usual field strength tensors. Two terms in this Lagrangian are responsible for mixing the gauge bosons: there is the usual mass mixing ( $\mathcal{L} \sim \Delta m^2 Z_\mu X^\mu$ ) which arises when the SM Higgs fields are charged under the  $U(1)_X$ , and the kinetic mixing term ( $\mathcal{L} \sim \frac{1}{2}\sin\chi X_{\mu\nu}B^{\mu\nu}$ ) which is allowed only because for abelian groups the field strengths are themselves gauge-invariant.

Taking the Lagrangian to its mass eigenbasis mixes the  $Z$  and  $X$  fields into mass eigenstates,  $Z_{1,2}$ , where we identify  $Z_1$  with the  $Z^0$  at LEP. One can think of going from the original basis to the physical basis as a two step process. First, a non-orthogonal transformation diagonalizes the

gauge kinetic terms, followed by a rotation which diagonalizes the mass terms. In the first of the two transformations, one gets the unexpected result that the effective charge to which one of the two  $U(1)$ 's couples is shifted. That is, in the interaction part of the Lagrangian one replaces:

$$\begin{aligned}\mathcal{L}_{int} &= \bar{\psi}_i \gamma_\mu X^\mu g_X x_i \psi_i \\ &\longrightarrow \bar{\psi}_i \gamma_\mu X^\mu \left( \frac{g_X x_i}{\cos \chi} - g_Y y_i \tan \chi \right) \psi_i\end{aligned}\quad (6)$$

where  $x_i$  and  $y_i$  are the  $U(1)_X$  charge and hypercharge of  $\psi_i$ . After the rotation, the mixing angle,  $\xi$ , will depend both on  $\Delta m^2$  and  $\sin \chi$ :

$$\tan 2\xi \propto \Delta m^2 + m_Z^2 \sin^2 \theta_W \sin \chi \quad (7)$$

and the interaction of  $Z_1$  with matter is given by:

$$\begin{aligned}\mathcal{L}_{Z_1} &= \bar{\psi}_i \gamma_\mu Z_1^\mu \left[ \frac{g_Y}{\sin \theta_W} (T_{3i} - Q_i \sin^2 \theta_W) \cos \xi \right. \\ &\quad \left. + \frac{g_X}{\cos \chi} (x_i + \delta \cdot y_i) \sin \xi \right] \psi_i\end{aligned}\quad (8)$$

where  $\delta = -(g_Y/g_X) \sin \chi$ .

Now, if one were to begin with a simple GUT at some high scale, then at the scale at which  $G_{GUT} \rightarrow U(1)_Y \times U(1)_X \times \dots$ , one has at tree level  $\sin \chi = 0$ . Then where does a non-zero  $\sin \chi$  come from? Consider  $U(1)$  mixing induced by loops, with  $X_\mu$  and  $B_\mu$  on the external legs and charged matter running in the loop. The polarization tensor will have the form:

$$\Pi_{XY}^{\mu\nu} = \frac{1}{6\pi^2} x_i y_i \log \left( \frac{m_i}{\mu} \right) [k^\mu k^\nu - k^2 g^{\mu\nu}] \quad (9)$$

for the  $i$ -th particle in the loop. This operator in turn generates a term in the Lagrangian  $\frac{1}{2} \sin \chi B_{\mu\nu} X^{\mu\nu}$  where we identify

$$\sin \chi = \frac{1}{6\pi^2} \sum_i x_i y_i \log \left( \frac{m_i}{\mu} \right). \quad (10)$$

Clearly if  $\sum_i x_i y_i = 0$  for degenerate particles then no mixing is induced, and this is often approximately true in GUT's. However, if the sum is non-zero, then one can resum the logarithms in  $\sin \chi$  from the GUT scale to the weak scale using the RGE's. (The details of the RGE's are found in Ref. [1].)

#### 4. $E_6$ and the $\eta$ -Model

Having developed the machinery for calculating  $U(1)$  kinetic mixing, let us now try it on a "realistic" GUT group, namely  $E_6$ . I will not try to argue here why  $E_6$  is particularly worth studying, since I will assume that most people are aware of its many useful properties. For now I need only describe  $E_6$  in so far as to note that  $E_6 \supset G_{SM} \times U(1)_X \times U(1)_\psi$ , where the last two  $U(1)$  factors are not contained in the SM. We are considering for this study the simpler final gauge group  $G_{SM} \times U(1)_X$ , so we identify  $U(1)_X$  as an arbitrary admixture of the two extra  $U(1)$ 's in  $E_6$ :

$$X_\mu = \cos \alpha \chi_\mu + \sin \alpha \psi_\mu. \quad (11)$$

It is a simple exercise to show that no such combination of  $U(1)_\chi$  and  $U(1)_\psi$  is leptophobic and can thereby be a candidate for explaining the LEP anomalies. (In fact, searches for the leptonic decays of the  $\chi_\mu$  and  $\psi_\mu$  gauge bosons place bounds on their masses above  $\sim 600$  GeV.)

However, let us add a new term to our Lagrangian, which for the time being will be simply a phenomenological parameter, namely a non-zero  $\delta \sim \sin \chi$  as in Eq. (8). We then fit all the LEP data, including  $R_b$  and  $R_c$  (see Ref. [1] for a discussion of the fitting procedure) to calculate  $\chi^2$  likelihoods for the fits at each choice of  $(\alpha, \delta)$ . The result, expressed as 95% confidence levels are:  $\alpha = -0.89 \pm 0.06$  and  $\delta = 0.35 \pm 0.08$  (the SM is excluded at 99.5% in this fit). What is remarkable is that the fit has picked out a very particular subgroup of  $E_6$  called the  $\eta$ -model in which  $\tan \alpha = -\sqrt{5/3} \simeq -0.91$ . Among the experimentally interesting characteristics of the  $\eta$ -model is that the anomalies of  $G_{SM} \times U(1)_\eta$  cancel if and only if entire **27**'s of  $E_6$  live at or below the  $U(1)_\eta$  breaking scale, which is presumably near the weak scale. Thus large numbers of new particles are expected at scales not very far above a few hundred GeV. And the reason that the  $\eta$ -model worked is that the combination  $\eta_i + y_i/3$  vanishes for SM leptons; that is, the  $\eta$ -model with  $\delta = 1/3$  is leptophobic!

Getting a realistic spectrum which will generate dynamically  $\delta \simeq 1/3$  through the RGE's is not necessarily possible. In fact, it turns out

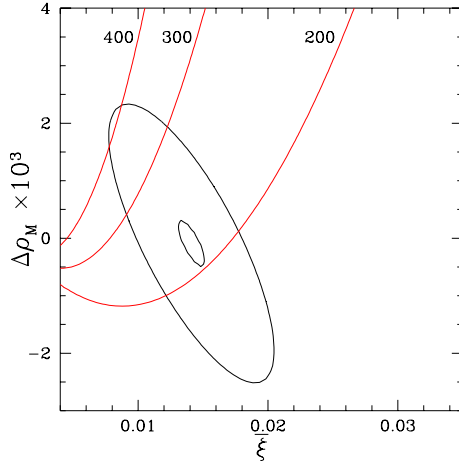


Figure 1. The 95% and 99% C.L. ellipses for the  $\eta$ -model with  $\delta = 0.29$ . The diagonal lines are contours of the  $Z_2$  mass.

that there are very few ways in which one can extend the  $\eta$ -model and keep it perturbative up to the GUT scale; however, one of these extensions (see Ref. [1] for details) can generate a value of  $\delta = 0.29$ , within the 95% bounds given above, providing a clear example of dynamical leptophobia.

In Figure 1, I show the 95% and 99% C.L. bounds for the  $\delta = 0.29$   $\eta$ -model in the plane of  $(\Delta\rho_M, \bar{\xi})$ , where  $\Delta\rho_M$  is the contribution to the  $\rho$ -parameter due to  $Z$ - $X$  mixing and  $\bar{\xi} = (g_X \sin \theta_W / g_Y) \xi$  is a rescaled  $Z$ - $X$  mixing angle. Cutting across the ellipses of constant  $\chi^2$  are contours of the  $Z_2$  mass. Rather interestingly, we find that the  $\eta$ -model predicts rather light  $Z_2$ : at 95%,  $200 < m_{Z_2} < 240$  GeV (at 99% C.L. the mass approaches the LEP  $Z^0$  mass).

### 5. $Z_2$ Signals and Searches

Traditional methods for searching for and excluding  $Z_2$  candidates are clearly untenable here. One usually produces new gauge bosons through their interactions with hadrons, but observes their decays through leptons; this decay channel

is simply far too small for a leptophobic model. And although the  $Z_2$  will decay to jets, those jets are overwhelmed by QCD backgrounds. To date the best bounds on  $Z_2 \rightarrow jj$  come from the UA2 Collaboration which was unable to rule out any significant portion of the mass/coupling range considered here. It has also been suggested [6] that the  $Z_2$  could be observed in associated production with a SM gauge boson, with  $Z_2 \rightarrow b\bar{b}$ ; here signals and backgrounds are small, but the ratio is close to one.

Finally, it has been realized that low-energy experiments might provide a strong bound on these extra  $Z$  models [7]. In particular,  $\nu N$  scattering and atomic parity experiments can provide an additional window on  $Z$ - $X$  mixing. For example, the weak charge of cesium is already  $1.2\sigma$  below the SM value, while the leptophobic models discussed here all tend to worsen the disagreement. However, it is easy to see that in the limit  $m_{Z_2} \rightarrow m_{Z_1}$ , all  $Z_2$  contributions to both low-energy extractions fall to zero, leaving only the SM prediction. (This is because both processes require a leptonic coupling at one vertex.) Thus, we are surprised to learn that not only is a light ( $\sim m_{Z_1}$ )  $Z_2$  allowed, but it might even be preferred!

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